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Simulation Case-study on Outdoor Air Quality Demand Controlled Ventilation

De Jonge Klaas, Ir-Arch **Moyaert Kenneth, Eng** **Laverge Jelle, PhD**
ASHRAE Member

ABSTRACT

Ventilation systems assume that the outdoor air quality is better than the indoor air quality at al times as they use outdoor air to dilute pollutants emitted by humans, activities, the building itself and other objects. However, the outdoor air quality is not always as clean as assumed. Traffic, industry and agriculture can pollute the outdoor air making the outdoor air also a source of certain unhealthy pollutants indoors. This challenges the beforestated assumption as in this case less ventilation would lower this source of pollution to the indoor environment.

A reference apartment for Belgium is simulated considering 4 categories of outdoor pollutants (NO2, Ozone, PM2.5 and PM10 for a street in the city-center of Antwerp, Belgium provided by airchecker) and two indoor pollutants generated by the 4 occupants and their activities (CO2 and H20). In this apartment, 3 variations of a control algorithm both taking into account the outdoor- and indoor air quality are simulated and compared to a control algorithm only taking into account the indoor air quality. Results are evaluated for three aspects: health, comfort and energy use. The system that does not consider outdoor pollution can safeguard the comfort of the occupants the best but also leads to the highest energy consumption and highest exposure to unhealthy outdoor pollutants. For each other case, a trade-off is made between the three aspects. Allowing higher peak exposures to CO2 and H20 during times of unhealthy outdoor air quality leads to less energy use and less exposure to unhealthy outdoor air.

A clear potential for the consideration of outdoor air quality in demand controled ventilation systems can be concluded as not only health is improved but also energy is saved. In practice however, it will be nececarry to quantify the state of both the indoor air quality and the outdoor quality and compare these in a more holistic manner than presented in these results.

INTRODUCTION

Ventilation systems are installed in homes to safeguard the Indoor Air Quality (IAQ) of the home. By diluting substances released to the indoor air by indoor sources (eg. humans, building materials, activities) it prevents the accumulation of these substances to levels outside the range of comfort and below levels of exposure with negative health effects.

The first generation of ventilation systems are continuous airflow systems and have a clear downside: they use a lot of energy (ventilators) and during winter supply cold air to the building which needs to be heated regardless of the need for dilution. That is why Demand Controlled Ventilation (DCV) systems were introduced which use sensors to

Klaas De Jonge is a FWO-SB research fellow for the flanders research foundation (FWO) residing at the Buiding Physics Research group, Ghent University, Belgium (1SA7619N). **Kenneth Moyaert** is an industrial engineer, graduated at Ghent University in 2019. **Jelle Laverge** is an assistant professor at the Building Physics Research Group.

monitor the CO2 and H20 concentration, and adapt the airflow rates accordingly. Both these concepts of ventilation rest on the assumption that the outdoor air quality is always better than the indoor air quality. With recent developments in the continuous monitoring and modelling of pollutants in the outdoor air it became clear that this might not always be the case if you consider the **health aspect** of outdoor air quality and the related IAQ(Guyot, Walker, and Sherman 2019; Mortensen, Walker, and Sherman 2011). This paper describes the results of a simulation case-study of the Belgian reference apartment which includes pollutant concentrations in the outdoor air for O3, NO2, PM2.5 and PM10. The DCV system which monitors C02 and H20 levels inside is combined with controls accounting for the four outdoor air pollutants and evaluated on its performance in terms of comfort (CO2, H20), health (exposure to 03, NO2, PM2.5 and PM10) and energy use.

SIMULATION MODEL

The software used for simulations is CONTAM, a well-established contaminant and airflow simulations software developed by NIST (Dols and Polidoro 2015). The simulated building is the Belgian reference apartment inhabited by a family of 4 (2 adults, 2 children) and has been used and described in several previous studies and will not be elaborated on further in this paper (De Jonge, Janssens, and Laverge 2018; Laverge and Janssens 2013; Heijmans, Van Den Bossche, and Janssens 2007).

Boundary condition: outdoor air quality

The outdoor air concentration of four pollutant categories were provided by airchekr: Ozone (O3), Nitrogen Dioxide (NO2), PM2.5 and PM10 ('Aircheckr' n.d.). The data is obtained by intelligent processing of sensor network data, wheaterdata and statistical modelling. The data was made available for seven months (11/09/2017-8/04/2018) and thus the simulated time was limited to this period.

The results shown in this study uses data of a street in the city enter of Antwerp. The busy traffic in the city and the high density of the buildings leads to high NO2, PM2.5 and PM10 concentrations, mainly during rush hour. Ozone concentrations are low due to the fact that the traffic also emits NO to the air which in turn breaks down the ozone.

Control algorithms

Three control algorithms are implemented and compared in the model.

The first control algorithm (CA_ref) does not consider the outdoor air quality and will be used as a reference. The supply airflow rates for each room are a function of CO2 concentration in that room. Below the lower limit value of 350 ppm above the outdoor air concentration, the ventilation flow rate is kept at a minimum om 10% of the nominal flow rate. From 950pmm onwards, the ventilation flow rate is kept at the nominal flow rate. If the measured value is between 350ppm and 950 ppm, the ventilation flow rate is linearly interpolated. For H20, the exhaust flow rate of all extraction points are a function of the most critical H2O level of one of these rooms. The system will always keep the total supply and total extraction flow rate in balance by adjusting the lower rate proportionally to match the higher rate. Table 1 shows the limit values and corresponding airflow rates for CA_ref.

Table 1 Control Limit Values for Comfort

	H_20	CO_2
Lower limit value	35%	350 ppm
Upper limit value	70%	950 ppm
Maximum airfow rate	Nominal flow rate	
Minimum airflow rate	10% nominal flow rate	

The second control algorithm (CA_2) controls indoor H20 and CO2 levels the same way but adds an outdoor air quality check. When one of the four outdoor air quality pollutants surpasses a defined limit concentration, the system considers the outdoor air as unhealthy and ventilation flow rates are lowered to the minimum ventilation rate. By doing so, the temporarily unhealthy outdoor air is kept outside. The intervention values of the Belgian indoor air quality decree (*Binnenmilieubesluit* 2018) and WHO (World Health Organisation n.d.) are used as boundary concentration for each of the pollutants and shown in table 2.

Table 2 Guide and Intervention Values for Outdoor Pollutants

Pollutant	Guide value (μg/m³)	Intervention value (μg/m³)	Source
NO_2	20	40	IAQ Decree
O_3	40	78	IAQ Decree
PM2.5	10	25*	IAQ Decree, *WHO
PM10	20	50	WHO

The third control algorithm (CA_3) is an optimisation of the previous. In cases where the outdoor air concentration of one of the pollutants is above the defined boundary concentration for longer times, the CO2 concentration may rise to high levels during that period, with consequently a high chance of discomfort. This control algorithm anticipates on this potential issue by using an additional limit concentration for CO2. When this additional limit is exceeded, the system ignores the outdoor air quality check thus temporarily working as the first algorithm would do. This control algorithm was once simulated with an additional limit concentration of 950ppm (CA_3_950) and once with an additional limit concentration of 1200ppm (CA_3_1200).

EVALUATION

The second and third control algorithm are compared with the reference using 3 criteria: comfort, energy use and health.

The comfort criterion is evaluated by comparing the exposure of the occupants to CO2 and H20. To obtain the characteristic values (min,max, quartiles,..) of the system, the average is calculated of each of the characteristic values for each occupant. (e.g. the maximum exposure to CO2 attributed to the system is the average of the maximum exposure to CO2 of each of the 4 occupants). Important to note is that CONTAM allows H20 levels to go beyond 100% Relative Humidity (RH) as condensation on walls or windows is not considered.

The energy use is evaluated using the average ventilation supply flow rate over the simulated period. A lower average supply flow rate results in less cold air being supplied to the home (low ventilation heat losses) and less fan power needed over this period.

The health criterion is evaluated using the DALY approach (World Health Organisation 2016; Logue et al. 2012). By doing so, the relative health impact of the different pollutants is considered. To obtain this value, the average occupant exposure concentration of the 4 occupants for each pollutant is multiplied with a corresponding Unit Damage Estimate (UDE) value and scaled to 100000 people. The UDE-values are derived from Lehtomäki et al. and shown in table 3 (Lehtomäki et al. 2018).

Table 3 Outdoor Pollutant UDE-Values

Pollutant	UDE-value
NO2	6.79
O3	0.26
PM2.5	83.01
PM10	5.86

RESULTS

Figure 1 shows a boxplot of the occupants CO2 and H20 (crosses indicate 95-percentile). It shows that the reference system performs best if only comfort would be considered. The lowered ventilation flow rates during periods of bad outdoor air quality allow CO2 and H20 to accumulate resulting in a higher exposure to these pollutants. It also shows that the additional boundary introduced in algorithm 3 (CA_3) yields an improvement on comfort, a lower CO2 boundary setting yields better comfort.

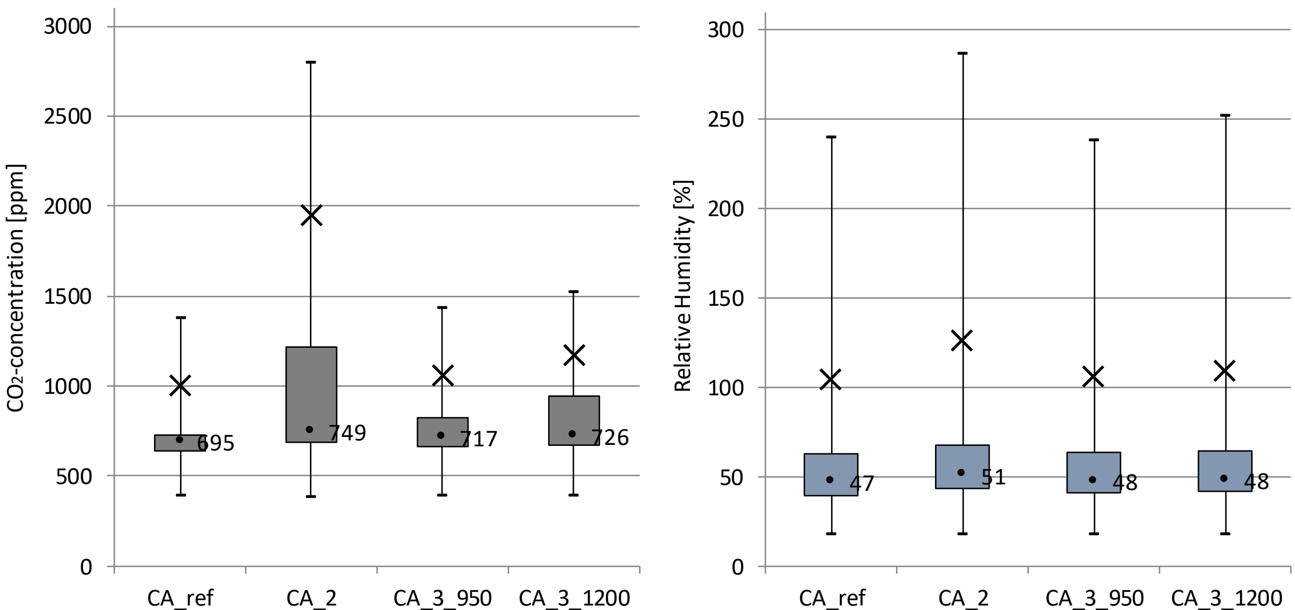


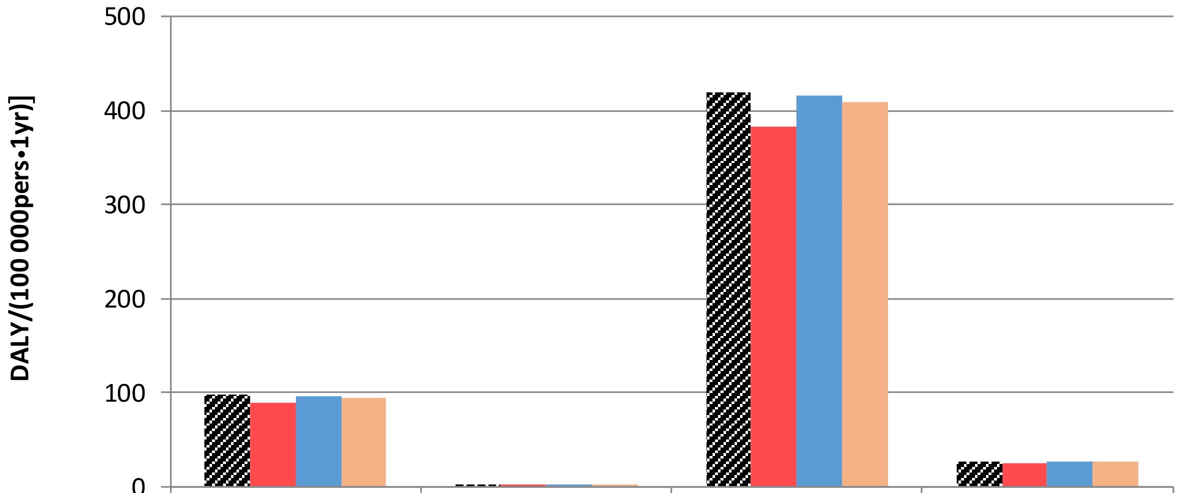
Figure 1 Boxplots with indication of 95th percentile (crosses) for the exposure to CO2 (left) and H20 (right) for each control algorithm.

Table 4 shows the average ventilation flow rate for all simulated systems and the relative change compared to the reference. The reference system has the highest energy consumption because the other systems all provide the minimal flow rates for longer periods of time due to the outdoor air quality check. When the additional CO2 boundary is added, the gain in energy savings the second algorithm (CA_2) has is partially undone because of the periods with CO2 concentration above this boundary. When the boundary is put at a higher value, more energy is saved.

Table 4 Average Suply Airflow Rates and Relative Change for each Control Algorithm

	Nominal	CA_ref	CA_2	CA_3_950	CA_3_1200
Avr Suply Ariflow Rate	273	100	70	89	82
Rel. change	63%	ref.	-44%	-12%	-22%

The evaluation of the health criterion is shown in figure 2. It shows the amount of DALYs attributed to each pollutant, for each system. In table 5 the total DALY count and relative increase/decrease with regards to the reference algorithm can be found. As expected, the reference algorithm and the second algorithm (CA_2) results in the highest and lowest total amount of DALYs respectively. The optimised algorithm (CA_3) scores somewhere between these two but even with a high CO2 boundary concentration undoes most of the savings. The relative improvement is very small, considering this the 'best case scenario' without the consideration of indoor sources of pollutants.



	NO2	O3	PM 2.5	PM 10
CA_ref	99	0.41	420	27
CA_2	89	0.45	382	25
CA_3_950	97	0.42	415	27
CA_3_1200	95	0.43	409	26

Figure 2 Dalys/100 000 pers. yr. attributed to each pollutant for each control algorithm.

Table 5 Total Daly Count and Relative Change for each Control Algorithm

	CA_ref	CA_2	CA_3_950	CA_3_1200
Total DALYs$_{/100\ 000pers.yr}$	546	497	539	531
Rel. change	ref.	-9.9%	-1.2%	-2.8%

Finally figure 3 shows a summary of all above results. The 100% line are the results of the reference system for all parameters. It clearly shows the trade-off being made between comfort, energy use and health for CA_2, CA_3_950 and CA_3_1200 compared to the reference. By allowing a relatively small increase in the chance of discomfort, the exposure to elevated levels of unhealthy outdoor pollutants can be lowered. During these periods the energy use is lowered and the system saves energy. Although exposure to ozone increases for the optimised systems, because of the low UDE value of this pollutant overall health improvements are made.

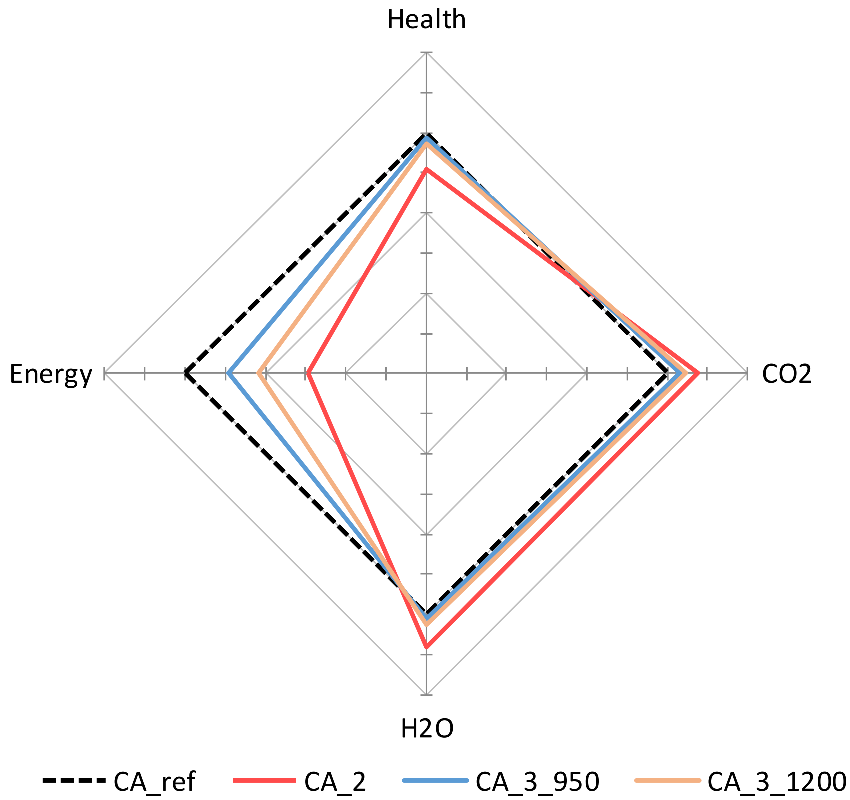


Figure 3 Relative change in energy use, health, average CO2 and H20 concentration relative to CA_ref for all other control algorithms.

CONCLUSION

The results show a clear potential for the consideration of outdoor air quality in residential demand controled ventilation systems. When indeed the outdoor air would be worse than the indoor air, at that point, for a certain period of time, ventilating less during that period is more advantageous and can be done without an enormous impact on comfort. The decrease in exposure to unhealthy indoor air however is also relatively small considering the fact that for this case study the best case scenario is assumed for the indoor air, namely no indoor sources, and for the outdoor air a worst case scenario is assumed, namely measurements of a busy street in a high density city in Belgium.

DISCUSSION

Important to note is the fact that indoor sources of pollutants other than CO2 and H20 are not considered in the simulation. Activities, building materials and furniture are all sources of potentially hazardous pollutants (e.g. VOCs, Ozone) and is ongoing research (De Jonge, Janssens, and Laverge 2019; De Jonge and Laverge 2019b; 2019a). The statement above is only correct if the outdoor air quality is indeed worse than the indoor air quality. In practice, the assessment of the quality of indoor/outdoor air however should be made considering more factors/pollutants then solely the outdoor air concentration of the four pollutants considered in this research.

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NOMENCLATURE

IAQ	=	Indoor Air Quality
O3	=	Ozone
NO2	=	Nitrogen Dioxide
NO	=	Nitrogen Oxide
PM	=	Particulate Matter
H20	=	Humidity, Water Vapor
CA	=	Control Algorithm
DALY	=	Dissability Adjusted Life Year
WHO	=	World Health Orginazatoin
UDE	=	Unit Damage Estimate

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